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SEDIMENT PATTERNS OF THE INTERTIDAL ZONE IN THE FIRTH OF CLYDE: VISUALISATION OF BIOLOGICAL, CHEMICAL AND PHYSICAL EFFECTS

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ABSTRACT

Intertidal environments consist of rocky, sandy, and muddy ecosystems. The sandy and muddy ecosystems together constitute intertidal sedimentary ecosystems. These are all dynamic environments that are affected by physical, chemical and biological processes, and they experience a number of changes during each diurnal tidal cycle and are also affected by lunar and seasonal changes. In sedimentary ecosystems, these include physical changes in sediment patterns due to water current and wave action, which form sand bars and ripples. Within the sediment column, particle size and packing affect the shear strength, pore size and water content of sediments. Chemical processes such as the oxidation-reduction potential (Eh) and the pH of the sediment determine the aerobic state of sediments. The activities of microorganisms in breaking down organic matter also play an important role. This is particularly noticeable during macroalgal decomposition.

Infaunal and epifaunal invertebrates, together with a number of vertebrates play a central role in the functioning of the intertidal sedimentary ecosystem. Their biological activity in and on sediments contributes significantly to the modification of the physical and chemical properties of sediments, and conversely the physical and chemical properties of sediments often determine which biological groups colonise and are active in these environments. This is an interacting system, in which benthic organisms ranging from microorganisms to macrofauna, fish, and birds affect the physical and chemical state of sediments, and the physical and chemical state of the sediments affects the biological activities of microorganisms, macrofauna, fish and birds.

In this paper we describe results of long term studies of an intertidal region at Ardmore Bay in the Clyde estuary, our objectives being to review for the professional and amateur marine scientist the muddy sandy environments that together make up the intertidal sedimentary ecosystem. The work reported here has been conducted over many years by members of the Biosedimentology Unit at the University of Glasgow, together with colleagues from the Department of Civil Engineering, and recently from the Department of Chemistry, and from the Centre of Excellence in Marine Biology at the University of Karachi, Pakistan. The paper illustrates some of the effects of physical, chemical and biological processes in a sedimentary context, highlighting the nature of sediment patterns as a principal consequence of sediment-benthos interactions.

INTRODUCTION

Intertidal zones between high and low tide are one of the most easily accessible, and also one of the most varied marine environments associated with the coastal zone. They range from steep rocky outcrops, to sandy and muddy beaches, shingle and saltmarshes, and contain a wealth of micro-environments and of animal and plant species (Reise, 1985; Meadows & Campbell, 1988; Mathieson & Nienhuis, 1991; Little & Kitching, 1996). As a result, they have been a source of detailed scientific study since at least the early nineteenth century. Recent studies have addressed a host of important ecological questions, including studying the taxonomy and biology of meiofauna in sediments, investigating the nature of predator-prey relationships between macrobenthos on rocky shores, and analysing community structure and function (Cadee, 1976, 1979; Frostick & McCave, 1979; Newell, 1979; Carney, 1981; Grant, 1983; Reise, 1985; Jenkins & Rae, 1997; Black *et al.*, 1998; Horn *et al.*, 1999; Widdows *et al.*, 2000; Consalvey *et al.*, 2004; Olaffson & Paterson, 2004; Roast *et al.*, 2004; Consalvey *et al.*, 2005; Deloffre *et al.*, 2005; Armitage & Fong, 2006; Orvain *et al.*, 2006; Paarlberg *et al.*, 2005; Siebert & Branch, 2006).

One of the most interesting areas that are currently being analysed, is the way in which physical processes and biological activity define the temporal and spatial structure of the intertidal zone – especially in sedimentary environments. Many investigations show how wind force, current speed, tidal range, and the activities of birds, fish, invertebrate macrofauna, meiofauna, and microorganisms interact with each other, to effectively determine this structure. These interactions are present on any intertidal area, however they are especially obvious around the coasts of the Clyde sea area and Firth of Clyde this sentence needs modifying because of the varied nature of exposed and sheltered environments in the region.

In the current paper we provide a series of examples and interpretations of physical, chemical and biological effects that are readily observable by close inspection of the surface and infrastructure of sediments, our aim being to provide for the non-specialist a guide to patterns on the sediment surface and their biological and physical causes. In order to do this, however, we need to provide a general background to some of the detailed processes that interact together in the intertidal zone, based on our work in the Firth of Clyde and Clyde Sea area.

Over a period of 30 years, we and our colleagues have been studying intertidal sedimentary ecosystems at Ardmore Bay and related intertidal ecosystems in the Firth of Clyde and have built up a comprehensive understanding of the physical, chemical and biological processes and their interactions occurring in these ecosystems (Meadows & Tait, 1985, 1989, Tufail, 1985; Meadows & Tufail 1986; Meadows & Shand, 1989; Tufail *et al.*, 1989; Meadows *et al.*, 1990; Muir Wood *et al.*, 1990; Meadows & Hariri, 1991; Meadows & Meadows, 1991; Meadows *et al.*, 1994; Muir Wood *et al.*, 1995; Meadows *et al.*, 1998a, 1998b; Shaikh, *et al.*, 1998; Carrasco *et al.*, 2002; Murray *et al.*, 2002). In this paper, therefore, we use Ardmore Bay as a source of material that will enable non-specialists to understand some of the complex processes and interactions occurring in and on sedimentary environments of the intertidal zone more generally.

MATERIALS AND METHODS

The materials and methods that have been used to produce most of the data presented in this paper have been described in detail elsewhere, and are too complex to cover fully here (Meadows & Tufail 1986; Meadows & Shand, 1989; Meadows *et al.*, 1989; Tufail *et al.*, 1989; Meadows *et al.*, 1990; Muir Wood *et al.*, 1990; Meadows & Hariri, 1991; Meadows & Meadows, 1991; Meadows *et al.*, 1994; Muir Wood *et al.*, 1995). However a brief summary of the main points will be of help.

Standard intertidal survey techniques of quadrat sampling using quarter metre quadrats, together with line transects have been Employed. Shear strength, redox potential, pH, particle size, pore size and the abundance of infaunal species of invertebrates are measured in the quadrats and along the line transects. These provide information on the detailed physical and chemical properties of the sediments and of the infaunal species.

Shear strength, which is a measure of the binding capacity, cohesion or strength of the sediment is measured at the surface of the sediment using a Geonor fall cone apparatus, and down the sedimentary column using a Pilcon vane. The Geonor fall cone releases a metal cone onto the surface of the sediment, and the depth of penetration of the cone into the sediment is measured. The Pilcon vane apparatus consists of a crossed vane on the end of a long metal rod. This is pushed progressively into the sediment, readings being taken every 5 to 10 cm vertically, by measuring the torque or twist needed to break the sediment, readings being taken on a circular torque disc at the top of the rod. Field data from both pieces of apparatus are converted to kN/m^2 using standard equations. The units kilo Newton can be seen to be force per unit area, in other words they are technically a pressure. This pressure is the pressure that is required to break the surface of the sediment using the Geonor fall cone, or to fracture the sedimentary column using the Pilcon vane. At a very practical level, the deeper one's boots, bucket or walking stick penetrate the sediment, the lower the shear strength.

A quantitative assessment of the pore sizes in the interstices of the sediments, including the burrows of any small invertebrates living in the sediment can be estimated by water release curves. Water release curves were measured on intact sediment cores collected from the upper intertidal region at Ardmore Bay. The cores were collected using 83 mm ID by 55 mm tall glass core sleeves. In the laboratory, the cores were mounted on a Haines apparatus (Haines, 1930) consisting of a 100 mm ID grade 4 porosity sintered glass Buchner funnel connected to a burette manometer. Fine, acid washed sand was used beneath the sediment core to ensure good contact between the sediment core and the sintered plate. The core was saturated with seawater and measurements of water content were made up to water potentials of –10kPa. The water release curves were used to calculate pore size distributions.

The Eh (oxidation-reduction) or redox potential of sediments is measure of the oxidising or reducing nature of the sediment. Sediments at or near the surface are usually highly oxidised or aerobic. As one progresses down the sedimentary column, the sedimentary environment becomes progressively more anaerobic. The change occurs at different depths ranging from a few millimetres to many centimetres in the intertidal zone. The change is most obvious to the casual observer as a darkening of the sediment from light brown to dark brown or black, and when black as the smell of hydrogen sulphide – rotten eggs. Most larger invertebrates that burrow into sediment aerate their burrows by ventilating them with seawater from the water column when the tide is in. If they did not do this, they would be unable to live in the more anoxic layers of the sediment. However a number of highly specialised bacteria, the anaerobic bacteria can live under these conditions, and some can only survive under these conditions. A typical representative is the sulphate reducing bacterium *Desulfovibrio delsulfuricans*. The redox potential of a sediment is therefore an important parameter to measure in terms of assessing the overall oxidised or reduced nature of the sediment. It is also an indirect measure of the total organic content of a sediment, because the more organic material in the sediment the more anaerobic it becomes – by microbial leading to the decomposition of the organic material. Redox potential is measured using standard Eh electrodes and an Eh meter.

The pH or alkalinity f sediments is also important, but does not vary so much as Eh. It is measured using pH electrodes and a pH meter. Together, Eh and pH provide a useful quick assessment of the aerobicity and alkalinity of sediments, and Eh-pH diagrams are used to provide a visual picture of the chemical state of sedimens both intertidally and in sea water.

Particle size of sediments is measured by sieving dried sediment through a series of standard sieves of decreasing mesh size, the weight of sediment on each sieve then being used to provide statistics on the mean particle size, sorting, skewness and kurtosis of the sediment sample.

Infaunal invertebrates are sieved from fresh wet sediment using a sieve whose mesh size is 750 microns. The species are identified, and the number of individuals in each species counted to give estimates of abundance.

Some of the work referred to below derives from a detailed analysis of the chemical, physical and biological features of quarter metre quadrats that were taken along two fifty metre transects. The first of these was established in the upper intertidal region and covered a number of algal patches and patches of bare sediment. The second was established in the lower intertidal region, and was sited to cross three peaks and the two intervening troughs of the large sand waves there. These are referred to as the high tide and low tide sites.

RESULTS

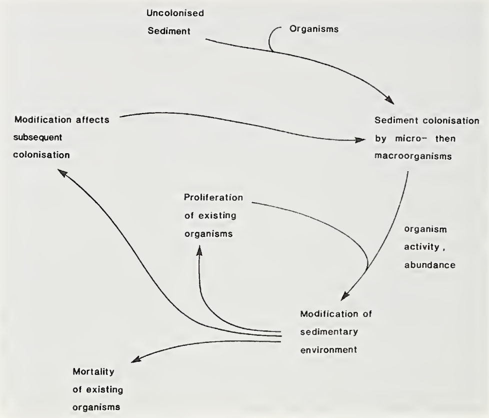
The nature of the sedimentary ecosystem

The simplest way of understanding how physical, chemical and biological interactions occur is to consider what happens when an uncolonised sediment is initially colonised by living organisms (Meadows & Tufail 1986) (Figure 1). The first step is for photosynthetic autrotrophic and heterotrophic microorganisms from the overlying water and surrounding sediments to be carried into the sediment by water moving through the pore water near the surface of the sediment. This initial colonisation is followed by the invasion of the sediment by the protozoa and very small invertebrate species that constitute the meiofauna. The meiofaunal species range in size from about 60 microns to a maximum of about 2 mm. Finally larger invertebrates colonise the sediment either as larvae settling on or in the superficial layers of the sediment, or by adult invertebrates burrowing into the sediment and constructing vertical and horizontal burrows. These are mainly annelids, molluscs and crustacea.

The bacteria, micro-algae, meiofauna and macrofauna modify the sediment by producing chemical extracellular polymeric materials (mucus), by feeding on organic material, and the larger macrofaunal invertebrates move through the sediment or construct burrows downwards into the sediment. These macrofaunal invertebrates include such organisms as the polychaete rag worm *Hediste (Nereis) diversicolor*, the crustacean mud shrimp *Corophium volutator*, and the edible cockle *Cerastoderma (Cardium) edule* and the mussel *Mytilus edulis* both of which are bivalve molluscs. All of these species alter the physical packing of the sediment, its water content and shear strength, its permeability and its Eh and pH. The organisms themselves proliferate, and many are eaten or die naturally, further complicating microscale ecological patterns within the sediment fabric.

The sedimentary ecosystem with its complex of interacting physical, chemical properties and its biological communities is an integrated whole, that varies from place to place in the intertidal zone, depending on organic input, degree of exposure, particle size, fresh water input and vertical position in the tidal zone. It can be viewed as a sediment benthos system in which all parts affect each other (Meadows & Tufail, 1986) (Figure 2). The abundance and activity of the microorganisms, meio and micro fauna and macrobenthos (invertebrates and macroalgae), interact and modify the chemical and physical processes taking place within the sedimentary column, and vice versa. This system in turn exports and imports organisms and chemicals to and from the overlying water column. The system is therefore complex, and even now its details are only understood in outline, as Murray *et al*., (2002) have pointed out recently. These authors consider the global scale of the system in all marine environments, ranging from the intertidal zone, through the continental shelves surrounding the major land masses, to the abyssal plains that cover half of the planet. They also draw attention to the importance of considering microscale effects and their impact on ocean ecosystems, and to the central role played by the extracellular polymeric material (mucus) secreted by many organisms that live on the sediment surface and within the sediment fabric.

Figure 1. Colonisation by biological species and the subsequent effects of biological activity on the sedimentary environment (Meadows & Tufail, 1986).

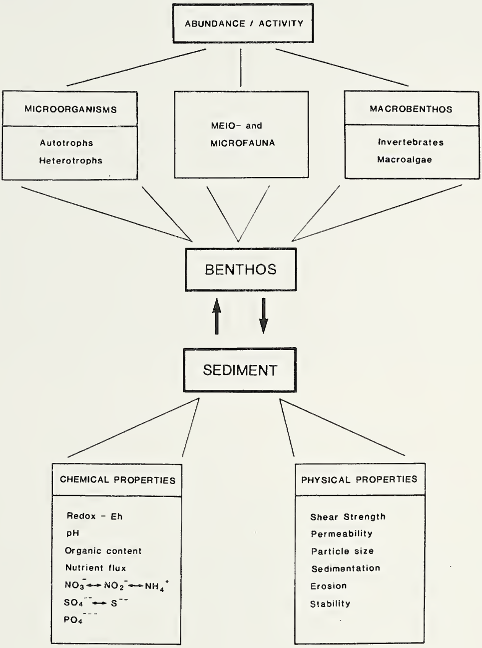


Ardmore Bay

Ardmore Bay, where many of the observations and measurements referred to in this paper have been made, is on the northwest side of Ardmore Point on the northern side of the Clyde Estuary near Helensburgh (National Grid NS 320 792). It has a number of distinct sedimentary ecosystems within it that provide a natural laboratory in which to conduct field experiments and to undertake surveys (Figure 3). Figure 4 shows the middle and lower intertidal zone of Ardmore Bay looking northwest towards low tide, with the town of Helensburgh in the distance. The very high abundance of the lugworm *Arenicola marina* is indicated by the large number of faecal casts of the lug worm *Arenicola marina* in the fore ground and middle ground. Figure 5 shows the middle and upper intertidal zone at Ardmore Bay, looking towards the east. The drainage channel down the beach, which is almost fresh water is clearly visible. Lugworm *Arenicola marina* casts are obvious in the foreground middle intertidal zone. Small rocks, erratics are visible in the upper intertidal zone of the beach in the middle distance. Figure 6 is a close-up view of the upper intertidal zone, looking towards the east. Is the following sent. Needed? The white house in the middle distance at the left can be seen in figure at the far left. The high tide zone is bounded by the salt marsh which is clearly visible in the middle of the photograph, with its saltings cliff about one metre high, separating the marsh from the intertidal low energy sedimentary ecosystem in the foreground.

In summer, the upper part of the intertidal bay is covered by patches of macroalgae – *Enteromorpha*, and the following is not seasonal by small boulders between half a metre and one metre in diameter. These latter are probably erratics left by retreating glaciers at the end of the last ice age. The patches of algal mats are one to five metres in diameter, and grow to this size in summer not sure of the following from underlying material. They die down in winter, but can still be located just below the sediment surface in a decayed state The Eh and pH of the algal and adjacent non-algal patches are significantly different, and this is associated with different biological communities that have been analysed in detail by Tufail *et al.*, (1989).

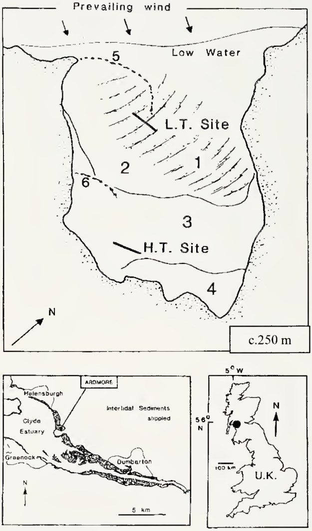
Figure 2. A model for the sediment/benthos ecosystem (Meadows & Tufail, 1986).



The middle region of the bay that occupies the central intertidal zone, is flat and contains a very large population of the mud-burrowing polychaete lugworm *Arenicola marina*, whose casts are highly visible at the sediment surface. The animal, which lives in a U-shaped burrow, feeds on small organisms and organic matter in the sediment that it takes in at the inhalant end of the U tube. It then excretes the sediment at the exhalent end of the U tube. The animal's faecal casts are most obvious when calm weather follows a storm. This may be because the storm causes wave action which fills the U tube with sediment that the animal then eats and excretes onto the sediment surface. The biology and ecology of Arenicola marina are described in detail by Wells (1945), and very recently by Tyler-walters (2006) who also provides key references for the species over the last 100 years.

The lower part of the intertidal zone in the bay has a number of large sand waves or dunes whose position is constant from year to year. The sand waves are covered twice a day by the diurnal tides and when not covered by the tide, except on very hot summer days. They are almost certainly produced by wave action caused by the prevailing westerly winds. The waves are a very characteristic feature of this part of the beach, and their sediment is coarser and more aerobic than sediment in the middle and upper intertidal zone of the beach. The troughs of the sand waves are almost always covered with one to five centimetres of sea water, even at low tide. The peaks of the sand waves are completely drained every tidal cycle. There is therefore a significant difference between the communities of animals that live in these two sedimentary ecosystems – the troughs and the peaks of the sand waves (Tufail *et al.*, 1989).

Figure 3. Location of the Clyde Estuary in the UK (right hand lower map), and of Ardmore Bay in the Clyde Estuary (left hand lower map). The upper map shows the general shape and main areas of Ardmore Bay. L.T. Site = site of the lower intertidal 50 metre transect. H.T Site = site of upper intertidal 50 metre transect. The lengths of the transects are exaggerated on the diagram to show their position.
1= area of sand waves. 2 = area of flat sand. 3 = area of algal mats and muddy sand. 4 = area of algal mats and muddy sand interspersed with small boulders. 5 and 6 = two rows of boulders that are almost certainly man-made. These are probably fish traps (yairs). (Tufail *et al.*, 1989)



Tufail *et al.* (1989) conducted a detailed analysis of the high tide and low tide regions of Ardmore Bay, by sampling along two 50 metre transect lines at one meter intervals. The differences between the two areas are very distinct, the high tide region being dominated by the algal mats, and the low tide region by the large sand waves. This is also apparent in the levels of the water table at the two sites.

The authors measured shear strength, redox potential, and the abundance of eight species of macrobenthic invertebrates inhabiting the sediment. Statistical correlation analyses and variance ratio tests of the relationships between the abundance of the macrofaunal invertebrates, redox potential and shear strength, showed interesting patterns. Variability between sediment parameters and between species abundance was higher at high tide than at low tide. However there were fewer significant correlations between sediment parameters and species abundance at high tide than at low tide.

The measured abundances of the individual species allowed diversity indices (Shannon Weiner and Simpson) to be calculated for the animal communities in the two areas of the beach. Community diversity as measured by these two indices was higher along the high tide transect than along the low tide transect. This may have reflected the greater availability of food in the form of organic material and small meiofauna at the high tide transect. There was more variability in the indices at the low tide transect than at the high tide transect. This is probably caused by the relatively large vertical difference between the peaks and troughs of the large sand waves.

Figure 4. The middle and lower intertidal zone of Ardmore Bay looking northwest towards low tide, with the town of Helensburgh in the distance. The very high abundance of the lugworm *Arenicola marina* is indicated by the large number The faecal casts of the lug wogrm *Arenicola marina* in the for ground and middle ground.

Figure 5. The middle and upper intertidal zone at Ardmore Bay, looking towards the east. The drainage channel down the beach, which is almost fresh water is clearly visible. Lugworm *Arenicola marina* casts are obvious in the foreground middle intertidal zone. Small rocks, erratics are visible in the upper intertidal zone of the beach in the middle distance.

Figure 6. The upper intertidal zone at Ardmore Bay, looking towards the east. Close-up view. The white house in the middle distance at the left can be seen in figure at the far left. The high tide zone is bounded by the salt marsh which is clearly visible in the middle of the photograph, with its saltings cliff about one meter high, separating the marsh from the intertidal low energy sedimentary ecosystem in the foreground.

Figure 7. The common mussel, *Mytilus edulis*, growing on sediment and small boulders on the north side of Ardmore Bay.

Physical and chemical patterns in sediments

Figure 8 shows the difference in the topography of the upper intertidal and lower intertidal areas of the beach along the two fifty metre transects (Tufail *et al.*, 1989). The peaks and troughs of the large sand waves in the lower intertidal region of the beach are obvious, and can also be seen in the upper map in figure 3. This demonstrates clearly that the high tide area is relatively flat compared with the large vertical variation in sediment height across the peaks and troughs of the sand waves in the low tide area.

The formation of sand bars, sand waves, and sediment ripples under water has received intense study over many years. However it is still not clear why these structures develop, except to state that they are caused by an interaction between the velocity of water currents in the boundary layer above the sediment and the sediment surface itself. There is also a very significant effect of sediment particle size. Finer sediments form sediment waves or ripples at much slower water velocities than coarser sediments. Furthermore as the velocity increases, the waves and ripples are flattened again. A similar effect occurs at the air-water interface at sea, where waves are produced by wind action up to a wind speed of about force 9 or 10, only to be flattened as the wind increases to force 11 and beyond – a sobering experience for those who have oceanic sea experience in research vessels.

At a very local level, and at relatively low horizontal water velocities, ripples are often present on sand in the intertidal zone. Figures 9 and 10 illustrate this at Ardmore Bay. Figure 9 shows ripples of wavelength c. 7.14 cm, that have been formed in the middle of the intertidal zone. The tops of these ripples have been flattened subsequent to their formation, both the formation and subsequent flattening taking place during the period that the sediment is covered by water. The close-up photograph in figure 10 is interesting. It shows unusual microscale erosion channels that appear to be developing along the top of the ripples. These are at a frequency of c. 1.2 cm, and may represent the initiation of ripple migration distruction or flattening. The phenomenon needs further investigation. There is also an asymmetry of the ripples in this photograph with the slopes to the right of the peaks being longer and of lower angle than those to the left of the peaks. This effect is most obvious in the left and right of the central ripple peak. This may represent the beginnings of ripple migration towards the left, with avalanching taking place down the steeper face.

Figure 11 shows profiles of sediment shear strength in an algal mat area (left hand graph. Labelled A), and a non-algal mat area (right hand graph, labelled NA), on the transect in the upper intertidal region. In this figure, the upper line (full circles) in each graph is the peak shear strength (an initial reading at each sediment depth). The lower line (full squares) in each graph is the residual shear strength (a second reading at the same depth, taken immediately after the first). The increase in shear strength into the sediment is a characteristic of most marine sedimentary environments, and at Ardmore Bay is similar on all parts of the beach.

The pore size distribution obtained from field cores in the laboratory using Haines apparatus shows a small number of relatively large pores (>0.2 mm diameter) with the main distribution centred at 0.05 mm diameter down to the limit of the measurements at 0.025 mm diameter These pores corresponded to 11% of the total core volume (Figure 12). The small number of large pores probably represents the U shaped burrows of the mud shrimp, *Corophium volutator*. The smaller pores may be burrows excavated by small immature Corophium, or by larger meiofauna. The role of meiofauna in this context was reviewed by the late Alan Reichelt in a seminal review article (Reichelt, 1991). Reichelt states that burrow formation in sediments is only known for a few groups of meiofauna, including species of burrowing copepods, nematodes, and tanaids. However these groups can occur in enormous numbers in sediments (Murray *et al.* 2002), and they probably play a very significant role in ventilating sediment both intertidally and in the subtidal. Water release curves as measured in the current paper, provide a quantitative assessment of the pore sizes in the interstices of the sediments which will include animal burrows, although in the field cores from Ardmore Bay the burrows do not appear to be behaving as simple cylinders, U-shaped or otherwise. The matter needs further analysis.

The redox characteristics and pH of the sediment is very different between the upper intertidal area and the lower intertidal area (figure 13). In the former, the presence of the algal mats provides additional heterogeneity. Within the algal mats, the sediment just below the surface has a very low Eh and is more acidic than sediment in the bare areas of the adjacent sediment. The effects of the low Eh are clearly visible as a very black layer of sediment just underneath the algal mats (Figure 14), where the previous year's growth of algae has been covered by sediment during the winter, and then becomes anaerobic by bacterial action on the decaying seaweed. The Eh of the sediment at low tide on the peaks of the sand waves is high, and the sediment has a more alkaline pH approximating to that of the overlying sea water.

Figure 8. Fifty-metre long transects at high tide and low tide, Ardmore Bay, showing level of water table in relation to the sediment surface. The difference between the two sites is very clear, with the low tide site being dominated by the large scale sand waves, whose wavelength is approximately 25 metres and amplitude approximately 20 cm. (Tufail *et al.*, 1989)

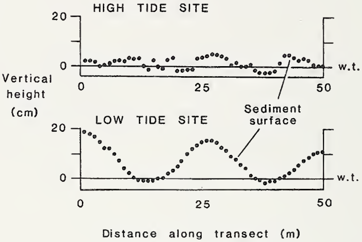


Figure 9. Small scale ripples on the middle of the intertidal zone and Ardmore Bay. The meter stick gives the scale. The wavelength of the ripples is approximately 7.14 cm. The tops of the ripples have been flattened by water movement subsequent to their formation. Both these events occur when the sediment is covered with water.

Figure 10. Close up photograph of ripples in the middle of the intertidal zone at Ardmore Bay. The ten pence piece, 2.5 cm diameter, gives the scale. The photograph, taken at a low angle of the sun, is approximately one-to-one. Note the interesting pattern of repeated micro-erosion channels at the top of the ripples. There are about 12 of these per 10 cm of ripple peak. Note also the asymmetry of the ripple, the slopes to the right of the two peaks being longer and of lower angle than those to the right of the peaks. This effect is most obvious in to the left and right of the central ripple.

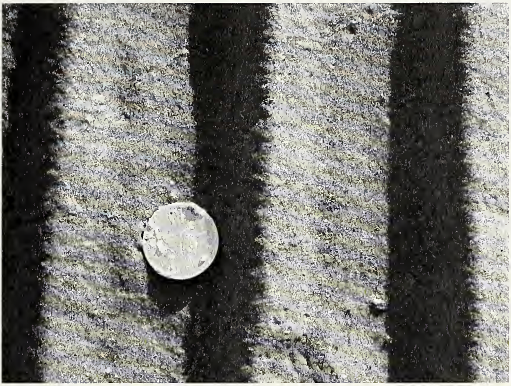


Figure 11. Profiles of sediment shear strength in an algal mat area (left hand graph. Labelled A), and a non-algal mat area (right hand graph, labelled NA), on the transect in the upper intertidal region.
x axis: depth into the sediment in cm. y axis: shear strength in kiloNewtons/metre^2.
The upper line in each graph is the peak shear strength (an initial reading at each sediment depth). The lower line in each graph is the residual shear strength (a second reading at the same depth, taken immediately after the first).

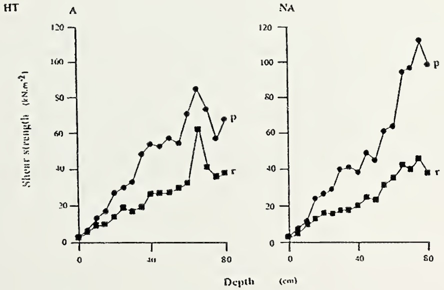


Figure 12. Moisture release curve (upper) and pore size distribution (lower) for two field cores, measured in the laboratory using Haines apparatus (Haines, 1930). The cores were obtained from the upper intertidal region in Ardmore Bay where mud shrimp, *Corophium volutator*, are abundant. The high values for pore volume at the extreme left hand side of the lower graph are probably caused by the burrows of adult mud shrimp *Corophium volutator*.

The relationship between the x axis values of water potential in the upper graph, and the x axis values of diameter classes in the lower graph (histogram) is a negative exponential. So the difference between the absolute sizes of the diameter classes on the x axis in the lower graph decreases exponentially from left to right along the histogram.

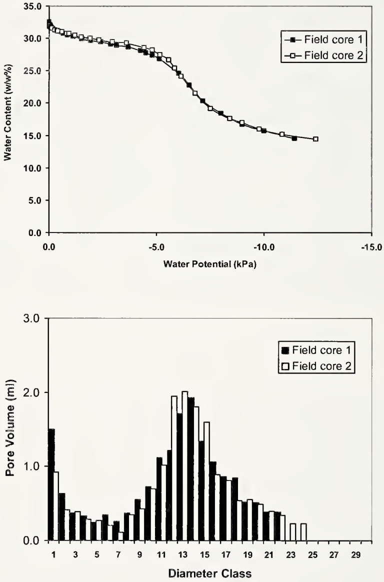


Figure 13. Eh/pH diagrams for the high tide site and low tide site at Ardmore Bay (Meadows and Tufail, 1986). The left hand diagram shows high tide data from algal mat and non-algal mat areas. The right hand diagram shows low tide data from the peak of a sand wave – the dune.

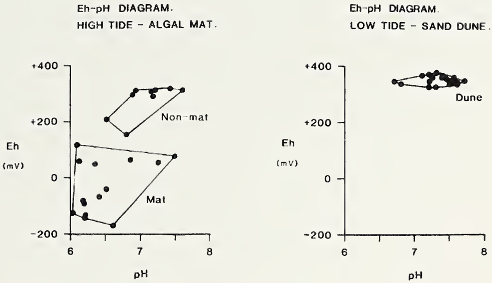
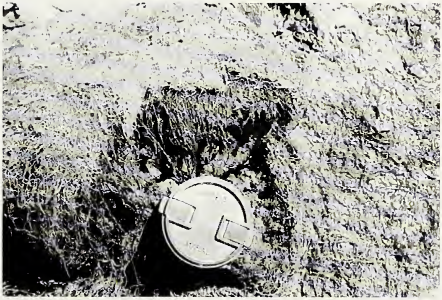


Figure 14. Algal mat growing on the surface of sediment in the upper intertidal region at Ardmore Bay. The intact algal mat at the sediment surface is around the upper part and periphery of the photograph, and in nature is a bright green. The highly anaerobic sediment and subsurface algal mat is in the centre and lower part of the photograph, and in nature is black. Scale is given by the camera lens cap, which is 5cm in diameter.



Biological patterns in and on sediments

Biological patterns in and on sediments at Ardmore Bay are distinctive, although many of them can be seen on other intertidal zones around the UK. They fall into two general categories, those that can be seen on the surface, and those that can only be seen when the sediment is dug into or cored. There is a very wide range of size in both categories These range from chains of microbial cells within the sediment itself that may be no more than 10 microns long (1000 micron = 1mm), to much larger scale modifications of the sediment surface which may extend for a metre or more.

We firstly describe the smallest effects that we have recorded, and then illustrate progressively larger sized biological patterns. One of the most dramatic points that becomes immediately apparent, is that the effects of biological activity and the resultant patterns in or on the sediment are clearly visible at all scales – even if it may need a scanning electron microscope or light microscope to visualise them. Figure 15 shows some of the microscopic effects. The left hand photomicrograph shows the network of secretions that are produced by a number of burrowing organisms, in this case the ragworm *Hediste (Nereis) diversicolor*. Sand grains can be seen in the lower part of the photomicrograph (Meadows *et al.*, 1990). These secretions consist of extracellular polymeric material, or mucus, that bind sediment particles together. They are often used by animals during the construction of their burrows. The right hand photomicrograph shows a typical community of microorganisms that grows at or just below the sediment surface (Meadows & Tufail, 1986). In this instance the two types of microorganisms are photosynthetic, the rope-like blue green algae and the barrel-shaped diatoms.

At a slightly larger scale within the sediment, burrows produced by invertebrate infauna that live in the sediment column can be demonstrated by using resin casts, and also by breaking a sediment using a spade on the shore. Figure 16 is a photograph of a resin impregnation of sediments from an intertidal area at Langbank on the southern shore of the Clyde Estuary, a little upstream from Ardmore Bay (Meadows & Tufail, 1986). The resin cast shows the complex system of burrows below the surface, even in this sediment where there are only three or four species.

Many of the biological structures and the burrows of individual animals can be observed by digging into the sediment. This is most effectively done by pushing a spade into the sediment at an angle of about 30 degrees from the vertical, and then breaking the sediment by levering the spade downwards towards you, until it lies almost flat. Figures 17 and 18 illustrate burrows exposed in this way. Figure 17 shows a natural burrow of the ragworm *Hediste (Nereis) diversicolor* on Ardmore Bay. The burrow runs vertically into the sediment and usually has one to three openings to the surface. The animal that constructed the burrow can be just seen in the burrow below the lens cap. The dividing line between the lighter aerobic sediment and the darker anaerobic sediment is termed as the Redox Potential Discontinuity Layer (RPDL) (Jickells & Rae, 1997). Redox potential decreases rapidly in this region, and the dark anaerobic layer is anaerobic enough for strictly anaerobic microorganisms to live there. Figure 18 illustrates natural burrows of the mud shrimp *Corophium volutator* on Ardmore Bay. The U shaped burrows run vertically into the sediment, and have two openings to the sediment surface – the tops of the U. The tops of the U are 1.0 to 2.1 cm apart in burrows constructed by adult animals. The darker sediment at the bottom of the exposed sediment section is anaerobic. The Redox Potential Discontinuity Layer separating the lighter aerobic sediment and the darker anaerobic sediment is again clearly visible.

Figure 15. Scanning electron microscope photomicrographs from Clyde Estuary sediments (Meadows & Tufail, 1986). Left hand photograph: particle binding secretions produced by the ragworm Hediste (Nereis) diversicolor (Meadows *et al.*, 1990); scale bar = 100 microns. Right hand photograph: blue green algae (rope-like structures) and diatoms (barrel shaped objects) in sediment interstices (Tufail, 1985); scale bar = 50 microns.

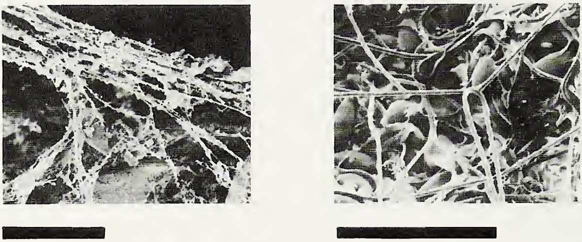


Figure 16. Resin impregnation casts of estuarine sediment from Langbank on the southern bank of the Clyde Estuary, slightly upstream from Ardmore Bay. 1 = the U-shaped burrows of the mud shrimp *Corophium volutator*. 2 = the deeper burrows of the ragworm *Hediste (Nereis) diversicolor*. 3 = a specimen of the burrowing bivalve, *Macoma baltica*. 4 = unidentified burrows, possibly of immature *Corophium volutator* or the small estuarine oligochaete *Tubifex costatus*. (Meadows & Tufail, 1986; Meadows et al., 1990).

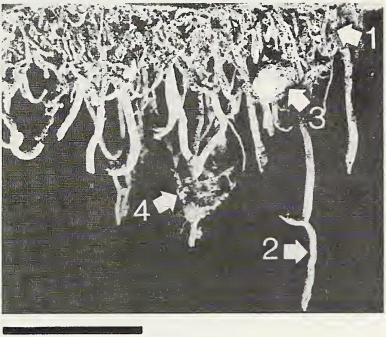


Figure 17. Natural burrow of the ragworm *Hediste (Nereis) diversicolor* on Ardmore Bay. The burrow has been exposed by pushing a spade into the sediment at an angle of about 30 degrees from vertical, and then breaking the sediment by levering the spade downwards until it lies almost flat. The scale is given by the camera lens cap which is about 5 cm in diameter. The burrow runs vertically into the sediment. The animal that constructed the burrow can be just seen in the burrow below the lens cap. The darker sediment in the lower part of the exposed sediment section is anaerobic. The dividing line between the lighter aerobic sediment and the darker anaerobic sediment is termed the Redox Potential Discontinuity Layer (RPDL).

Figure 18. Natural burrows of the mud shrimp *Corophium volutator* on Ardmore Bay. The burrows were exposed by pushing a spade into the sediment at an angle of about 30 degrees from vertical, and then breaking the sediment by levering the spade downwards until it lies almost flat. The scale is given by the camera lens cap which is about 5 cm in diameter. The U shaped burrows run vertically into the sediment, and have two openings to the sediment surface – the tops of the U. The tops of the U are 1.0 to 2.1 cm apart for each burrow. The darker sediment at the bottom of the exposed sediment section is anaerobic. The dividing line between the lighter aerobic sediment and the darker anaerobic sediment is termed the Redox Potential Discontinuity Layer.

Figures 19 illustrates the surface of sediment in the upper intertidal zone at Ardmore Bay as seen in close-up view. The low light angle enables the details of the surface structure to be seen clearly. The scale is approximately one-to-one. The larger raised cones are small casts of the lugworm *Arenicola marina*.casts. The smaller cones which cover the surface are the entrances to burrows of immature mud shrimps *Corophium volutator*.

Figures 20 and 21, taken during a Haines experiment, show that almost identical patterns of burrows develop in the cores that were taken from the field. In surface view (Figure 20) the larger holes are the openings of the U-shaped burrows of adult mud shrimp, *Corophium volutator*. The smaller holes are the openings of similar U-shaped burrows constructed by small immature *Corophium volutator*. Figure 21 shows how the internal structure and burrows mimic the field picture shown in figure 18.

Figure 19. Close up view of the surface of sediment in the upper intertidal zone at Ardmore Bay. The low light angle enables the details of the surface structure to be seen clearly. Theblack bar = 5 cm. The larger raised cones are the entrances to the burrows of adult mud shrimp *Corophium volutator*. The smaller cones which pepper the surface are the entrances to burrows of immature Corophium.

The polychaete lug worm *Arenicola marina* is very abundant on many intertidal muddy and sandy beaches, and also occurs subtidally. There are very large populations of *A. marina* on most parts of the intertidal region at Ardmore Bay (Figures 4, 5). The animal constructs a U-shaped burrow that on Ardmore Bay is between 15cm and 30 cm deep (Figure 22). The inhalant and exhalent entrances of the burrows – which are easily distinguished from each other by the pile of faeces at the exhalent entrance – can be seen on most parts of the beach. Burrows and animals can be seen by digging with a spade, however the digging process has to be done quickly because animals are adept at digging deeper into the sediment.

The animal usually lies at the bottom of the burrow when the burrow surface is exposed to the air. The difference in colour between the surficial aerobic sediment and the deeper anaerobic sediment can usually be seen quite clearly, especially towards high tide where the deeper sediment is very anoxic. The boundary between the two sediments is the Redox Potential Discontinuity Layer. The light aerobic sediment extends into the anaerobic layer as a cylinder around the burrow. This is because the burrow is ventilated by the actions of the animal, and oxygen in the water diffuses across the burrow lining. Animals feed sediment falling into the entrance area of the burrow as it ventilates the burrow. It passes the sediment through the gut, digesting organic matter and small organisms. The digested sediment is excreted as a coiled pile of faeces at the exhalent entrance to the burrow (Figure 23). The colour of this faecal sediment sometimes indicates that the animal has been feeding on sediment that has come from the anaerobic layers of the sediment, because it is dark brown or dark grey. As sediment is drawn into the inhalant entrance of the burrow, miscellaneous pieces of biological material such as small broken pieces of algae are taken in, and presumably eaten by the animal along with the sediment that it takes in (Figures 24 and 25).

Figure 20. Surface view of the sediment core that was used in the Haines apparatus (Haines, 1930). Two categories of burrow opening are clearly visible. The large ones are the openings of the U-shaped burrows of adult mud shrimp, *Corophium volutator*. The smaller ones are the openings of similar U-shaped burrows constructed by small immature *Corophium volutator*. These field cores when brought to the lab are completely drained of pore water.

Figure 21. Internal patterns of burrows of the core illustrated in figure 20. The burrows are those produced by the mud shrimp, *Corophium volutator*.

Figure 22. Diagram of large U-shaped burrow of the polychaete lugworm *Arenicola marina*. Note the inhalant and exhalent entrances to the burrow and the plug of faecal material, lying at the exhalent entrance. The animal usually lies at the bottom of the burrow when the burrow surface is exposed to the air. The difference in colour between the surficial aerobic sediment and the deeper anaerobic sediment is usually very obvious. The boundary between the two sediments, the Redox Potential Discontinuity Layer, is shown by the dashed line. The light aerobic sediment extends into the anaerobic layer as a cylinder around the burrow. This is because the burrow is ventilated by the actions of the animal, and oxygen in the water diffuses across the burrow lining. (Meadows & Campbell, 1988, p.119).

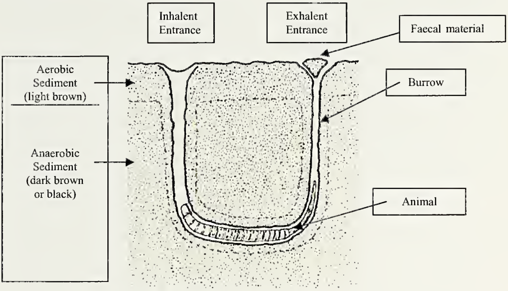


Figure 23. Pile of faecal sediment at the exhalent entrance of a burrow of the lugworm Arenicola marina. The ten pence piece (diameter 2.5 cm) gives the scale. The lower part of the pile has been eroded by water.
A small inhalant entrance (arrowed) with its surrounding cone can be seen indistinctly at the bottom left of the figure.

Figure 24. Inhalent entrance of the burrow of the polychaete lugworm *Arenicola marina* (bottom of the figure), at Ardmore Bay. Note the broken pieces of seaweed being taken into the burrow. Presumably the lugworm will ingest this with the sediment that it is eating. Note also the small then indistinct tubes. These are probably tubes of the small polychaetes *Pygospio elegans* or *Fabricia sabella*, both of which species are common on the intertidal at Ardmore Bay. The ten pence piece (diameter 2.5 cm) gives the scale.

Figure 25. Two inhalant burrows of the polychaete lugworm *Arenicola marina* at Ardmore Bay. The smaller tubes and small elevations on the sediment surface that are more obvious in the lower part of the figure are either the burrows of *Pygospio elegans* or *Fabricia sabella* (see figure 24). The ten pence piece (diameter 2.5 cm) gives the scale.

Traces made by organisms moving over or just below the surface of sediments are a common feature of muddy or sandy sedimentary environments in the intertidal zone, and these occur very regularly on the sediments at Ardmore Bay. The difficulty with these traces is that it is often unclear which type of organism or species has made them, unless one sees an individual in the process of making the trace. The trace illustrated in figure 26 is typical. It is clearly a trail caused by a small organism moving over or just below the sediment surface. The species is likely to be a small polychaete annelid or nemertine. Alternatively, it may be the surface trail of the small mud burrowing bivalve *Macoma balthica* that moves through the sediment just below the sediment surface. However the movement trails of *Macoma balthica* are usually gently curved – as seen in figure 30.
Macroalgae or seaweeds sometimes leave traces at the sediment surface. These are algal species that are either attached to small stones at the surface of the sediment, or that have been removed from intertidal rock surfaces by heavy wave action. As the algae lie on the surface of the sediment and are exposed to the flow and ebb of the tide, they are moved by the water and waves. When there is a reasonable depth of water above them, they float in the water column. As the tide falls and the water depth decreases, the plant lies on the sediment surface. It is at this point that the plant makes marks on the sediment surface caused by the receding tide moving the plant backwards and forwards. The resultant marks, which often appear like random scratches at the surface of the sediment, are not uncommon at Ardmore Bay, but are very obvious when seen. Figure 27 shows *Fucus* spp. probably *Fucus vesiculosus*, attached to a small boulder in the middle intertidal zone at Ardmore Bay. Streak marks on the sediment surface were made by the plant being moved by water as the tide receded. The weight of the plant has been enough to erode the ripples that are present elsewhere on the sediment surface.

Figure 26. Movement trail of an organism that has recently moved across the surface of the sediment. Ardmore Bay. The movement trace is about 3 mm in diameter. The organism that made trail is not known. It may be a small polychaete or nemertine, or possibly the small mud-burrowing bivalve Macoma baltica. The ten pence piece (diameter 2.5 cm) gives the scale.

Fish and birds also disturb the surface of the sediment, during feeding or while moving over the sediment under water, or when the tide has receded (Fog, 1967; Thiel, 1981; Madsen, 1988; Cadee, 1990; Cadee *et al.* 1994; Iribarne *et al.*, 2005). Small aggregations of shell material such as those shown in figure 28, have been seen from time to time on the intertidal zone at Ardmore. It is likely that these represent shell material regurgitated by birds Zonfrillo (personal communication 2004). In a recent email (Zonfrillo, personal communication 2007) he states "I'd think Gulls (Herring, Great Black-backed) might be responsible for regurgitating that cockle debris. Eider are another possibility. Shelduck eat mainly *Hydrobia*, but Eiders can handle *Mytilus* and probably small cockles in the gizzard, though usually it will come out the other end, they don't normally produce pellets!. If gulls use that area then it is more likely to be a coughed-up gull pellet, a Great Black-back (my best guess) will have the gizzard capable of grinding up thick shells. Sometimes they will swallow small stones to aid the process. I've found that kind of shell material, and starfish, in them elsewhere." Based on Zonfrillo's views and observations by the authors of birds feeding in the intertidal zone at Ardmore (Figure 29), the regurgitated material probably comes from one of the gull species.

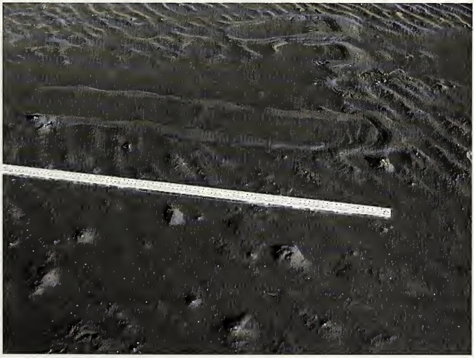
Figure 27. *Fucus* spp. probably *Fucus vesiculosus*, attached to a small boulder in the middle intertidal zone at Ardmore Bay. The small boulder is at the top of the figure. Marks made by the plant being moved by water movement as the tide receded are obvious. The weight of the plant has been enough to erode the ripples that are present elsewhere on the sediment surface. The ten pence piece (diameter 2.5 cm) just below the centre left, gives the scale.

Figure 28. Shell material either regurgitated or faecal. Largely consisting of fragments of the edible cockle *Cerastoderma (Cardium) edule.* The ten pence piece (diameter 2.5 cm) gives the scale.

Figure 29. Gull or duck footprints on the sediment surface in the upper intertidal region at Ardmore Bay. The curved track is made by the small bivalve Macoma balthica moving through the sediment just below the surface. The ten pence piece (diameter 2.5 cm) gives the scale.

The surface markings in the upper intertidal zone shown in figure 30 are probably caused either by benthic feeding birds or benthic feeding fish. Zonfrillo (2007 – personal communication) considers them to be caused by birds. Cadee (1990) records such patterns that of Black Headed gulls *Larus ridibundus* and Shelducks (*Tadorna tadorna*). Black Headed gulls make troughs up to 3 metres long and about 15 cm wide – this is very similar to the markings in figure 30. Shelducks make craters about 10 cm deep and up to 60 cm in diameter, and Eider ducks (*Somateria mollissima*) make similar craters. Cadee (1990) also records craters made by rays (*Hypotrema*), flounders (*Platichtys flesus*) and bream (*Abramis brama*). The authors of the current paper therefore consider that the most likely cause of the surface markings shown in figure 30 are either feeding troughs produced by Black Headed Gulls or feeding traces made by young ray or flounders,

Figure 30. Surface markings in the upper intertidal at Ardmore Bay. Either caused by benthic feeding fish or birds. See text for further details. The scale is given by the metre stick.



CONCLUSION

In this paper, we have attempted to provide an overall view of the intertidal sediment ecosystem together with a description of the complex web of physical, chemical and biological interactions that make it so interesting. It has been our objective to provide an account that allows the non-specialist to appreciate this complexity, and to visualise some of the effects that are obvious to a trained eye on one particular shore, Ardmore Bay, adjacent to and just northeast of Ardmore Point, in the Clyde Estuary. Visualisation is very important to the specialist as well as the non-specialist. Both can learn a great deal about a particular sedimentary ecosystem by walking over it, looking at it, and digging into it.

We began by taking a very general view of the organisms that live in or on sediments and how they colonise and modify the physical and chemical properties of the sediment (Figures 1 and 2). The geography of Ardmore Bay, and its general characteristics are shown in figures 3 to 7. The physical and chemical patterns in and on sediments are sometimes only demonstrable by field or laboratory experiments. In figure 8 we show how the low tide area is characterised by large sand waves, while at high tide (Figure 13) the presence of algal mats modify the chemical nature of the surface and subsurface sediment by changing the Eh and pH of the interstitial water. The shear strength profiles in figure 11 and the moisture release curves shown in figure 12 provide additional information that can also only be provided by field or laboratory investigation. In contrast, the ripples at the sediment surface illustrated in figures 9 and 10, together with the anaerobic sediment lying just below an algal mat shown figure 14 are observable on the shore by direct observation.

The biological patterns caused by the activities of microorganisms and animals in and on the sediment are usually more immediately obvious, unless they are microscopic. However the secretions produced by many burrowing invertebrates that bind sediment particles in their burrow linings, thus increasing the strength of the lining, can only be seen easily by scanning electron microscopy. We illustrate these in figure 15. The burrows themselves can usually be observed by digging into the sediment, or seen at the surface as burrow openings (Figures 17 to 25). On Ardmore Bay, the two dominant species in this context are the mud burrowing shrimp, *Corophium volutator*, and the lugworm *Arenicola marina*. Both are major bioturbators, moving large quantities of sediment during the construction and maintenance of their burrow systems. The burrows of both species can be observed by digging (Figures 17, 18, 21), and their openings are obvious on the sediment surface (Figures 4, 5, 19, 20, 23, 24, 25). Many smaller invertebrates can also leave tracks at or near the sediment surface. One such is illustrated in figure 27 and another in figure 30. Movement of seaweeds by tidal flow just as the tide leaves the sediment surface often also produce recognisable drag marks (Figure 27).

Fish and birds can cause major disturbance at the sediment surface or deposit material there. The regurgitated shell fragments of bivalve molluscs eaten by birds are very obvious when present (Figure 28). Gulls and ducks leave footprints, and they or fish may produce long tracks on the sediment that are very obvious even from a distance (Figure 30).

All of the above indicates that the intertidal sedimentary ecosystem is a dynamic one. Ardmore Bay is just one example of many such ecosystems where interactions between the physical and chemical properties of sediments and their living organisms produce a complex mix of processes. The effects of many of these processes can be seen within the sediment and at the sediment surface by direct observation on most intertidal muddy sand beaches.

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